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# ACCURACY OF STAR CLUSTER PARAMETERS FROM INTEGRATED UBVRIJHK PHOTOMETRY

A. Bridžius[1], D. Narbutis[1,2], R. Stonkutė[1], V. Deveikis[2] and V. Vansevičius[1,2]

[1] *Institute of Physics, Savanorių 231, Vilnius LT-02300, Lithuania*
*wladas@astro.lt*

[2] *Vilnius University Observatory, Čiurlionio 29, Vilnius LT-03100, Lithuania*

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**Abstract.** We investigate the capability of the *UBVRIJHK* photometric system to quantify star clusters in terms of age, metallicity and color excess by their integrated photometry in the framework of PÉGASE single stellar population (SSP) models. The age-metallicity-extinction degeneracy was analyzed for various parameter combinations, assuming different levels of photometric accuracy. We conclude, that most of the parameter degeneracies, typical to the *UBVRI* photometric system, are broken in the case when the photometry data are supplemented with at least one infrared magnitude of the *JHK* passbands, with an accuracy better than $\sim 0.05$ mag. The presented analysis with no preassumptions on the distribution of photometric errors of star cluster models, provides estimate of the intrinsic capability of any photometric system to determine star cluster parameters from integrated photometry.

**Key words:** techniques: photometric – methods: data analysis – galaxies: star clusters

## 1. INTRODUCTION

Broad-band photometric data of extragalactic star clusters are applicable to derive their evolutionary parameters via comparison with single stellar population (SSP) models. However, this procedure is restricted by the fact that in some parameter domains strong age-metallicity-extinction degeneracies (see, e.g., Worthey 1994) remain unsolved. For a study of broad-band color indices, most sensitive to various star and cluster parameters, see, e.g., Jordi et al. (2006) and Li et al. (2007).

It is known (Anders et al. 2004; Kaviraj et al. 2007) that infrared and ultraviolet passbands are helpful for breaking the age-metallicity-extinction degeneracies. In this respect infrared observations have the priority: in some atmospheric windows they are accessible for ground-based telescopes, while ultraviolet photometry shorter than 300 nm is possible only from space. In some extragalactic studies of star clusters published to date various combinations of optical and/or near-infrared passbands have been used (e.g., Kodaira et al. 2004; Hempel & Kissler-Patig 2004; Fan et al. 2006; Hempel et al. 2007; Narbutis et al. 2008; Pessev et al. 2008).

However, in comparison to photometry in the optical range, ground-based infrared photometry usually has larger errors due to variable humidity, and this

requires a careful calibration (e.g., Kodaira et al. 1999; Kidger et al. 2006). The reliability of secondary standards used for photometric calibration of wide field images, should be verified by several independent sources, if they are available (e.g., Narbutis, Stonkutė & Vansevičius 2006).

In the present paper we continue to investigate a possibility of determining star cluster parameters (age, metallicity and color excess) by comparison of their integrated color indices with the SSP models computed with the PÉGASE (v. 2.0; Fioc & Rocca-Volmerange 1997) code package. In our previous study (Narbutis et al. 2007b, hereafter Paper I) it was found that the *UBVRI* system enables us to estimate cluster parameters over a wide range of their values, when the overall accuracy of color indices is better than $\sim 0.03$ mag. In the following we discuss how the adding of the *JHK* passbands affects the accuracy of cluster parameter (age, metallicity and color excess) determination. We analyze degeneracies at various accuracy levels of photometry for the same values of cluster parameters as in Paper I.

In the similar study Anders et al. (2004) have used the so-called AnalySED method for determining cluster parameters with a different approach to the degeneracy problem. In Section 2 we discuss the main differences between the Anders et al. and our methods and note, that the parameter degeneracy analysis presented in this study is based on minimum assumptions.

## 2. THE METHOD

The analysis method used in this study is similar to that of Paper I. The SSP models were computed with the PÉGASE program package, applying its default options and the universal initial mass function (UIMF; Kroupa 2001). The integrated color indices in all pass-bands in respect to the $V$-band of SSP models were reddened by taking into account the dependence of color-excess ratio (e.g., $E_{U-B}/E_{B-V}$) on color index $B$–$V$ of SSP model and assumed color excess, $E_{B-V}$, applying the standard extinction law (Cardelli et al. 1989). The three-parameter (3-D) SSP model grid of $\sim 5 \times 10^5$ models was constructed at the following nodes: (i) 76 age, $t$, values from 1 Myr to 20 Gyr with a constant step of $\log(t/\mathrm{Myr}) = 0.05$;[1] (ii) 31 metallicity[2], [M/H], values from $-2.3$ to $+0.7$, with a step of 0.1 dex; (iii) 201 color excess, $E_{B-V}$, values from 0.0 to 2.0, with a step of 0.01.

The procedure of determination of cluster parameters ($t$, [M/H], $E_{B-V}$) was implemented as a C++ code in the data analysis and the graphing software package 'Origin' (OriginLab Corporation). It is based on a similar technique developed for star quantification by Vansevičius & Bridžius (1994), i.e., the comparison of the observed color indices of a star cluster with color indices of the SSP from the model grid. For this purpose we use the quantification quality criterion, $\delta$, calculated by the formula:

$$\delta = \sqrt{\frac{\sum w_i (CI_i^{\mathrm{obs}} - CI_i^{\mathrm{mod}})^2}{\sum w_i}}\,, \qquad (1)$$

where $CI_i^{\mathrm{obs}}$ stands for the "observed" color indices $U$–$V$, $B$–$V$, $V$–$R$, $V$–$I$, $V$–$J$,

[1] For the ages $< 12$ Myr the step was equal to 1 Myr. The SSP models for the ages larger than the oldest known globular clusters are used to avoid marginal effects.

[2] [M/H] was computed applying the approximation $[\mathrm{M/H}] = \log(Z/Z_\odot)$.

$V$–$H$ and $V$–$K$; $CI_i^{\rm mod}$ – the corresponding color indices of the SSP models from the grid; $w_i$ – the weights for the observed color indices.

We investigate the possibility to determine cluster parameters using the *UBVRIJHK* photometric system for 54 models taken from the SSP model grid as "observed" objects with the following parameters: $t = 0.02$, 0.05, 0.1, 0.2, 0.5, 1, 2, 5, 10 Gyr, [M/H] = 0.0, −0.7, −1.7 and $E_{B-V} = 0.1$, 1.0. Their color indices are denoted by $CI_i^{\rm obs}$, see Eq. 1. We have assigned the weights of $w_i = 1$ for $U-V$, $B-V$, $V-R$ and $V-I$ color indices, and $w_i = 1/9$ for $V$–$J$, $V$–$H$ and $V$–$K$ of the "observed" star clusters. Such weighting scheme assumes that the accuracy of the infrared *JHK* observations is $\sim 3$ times lower than that of the optical *UBVRI* – a typical condition in photometry of extragalactic star clusters.

Anders et al. (2004) have extensively analyzed the possibilities of their AnalySED method, which has a different approach to the degeneracy problem, comparing to the method presented in this paper. First, AnalySED is based on the comparison of observed magnitudes with the model magnitudes, while for the same aim we are using color indices. This allows us to avoid fitting of an additional free parameter – the cluster mass. Second, Anders et al. (2004) define the "observed" magnitudes of model clusters by assigning to them random errors. However, we did not apply "observation errors" to color indices, since it is reasonable to assume that the quantification quality criterion, $\delta$, reflects the effect of photometric accuracy sufficiently well. In general, $\delta$ represents the lowest possible average photometric error of all color indices, which in the case of real clusters can be larger, mostly due to the influence of crowding by contaminating field stars (e.g., Narbutis et al. 2007a). Therefore, the parameter degeneracy analysis presented in this study is based on minimum assumptions.

We have used several $\delta_{\rm max}$ values as the upper threshold levels of photometric errors. The cluster parameters were determined independently at each accuracy level by averaging the corresponding parameter values of SSP models at the grid nodes, which have $\delta \le \delta_{\rm max}$. The weights for the calculation of the parameter averages and the standard deviations were assigned 1 and $10^{-4}/\delta^2$ for the nodes with $\delta \le 0.01$ and $> 0.01$ mag, respectively.

Furthermore, for the parameter averaging we used only the nodes, which reside in a single continuous 'island' around the true cluster position in the 3-D parameter space of the SSP model grid. Boundaries of 'islands' at each $\delta_{\rm max}$ level were determined automatically by the *clustering procedure*, which finds discontinuities in the parameter space, starting from the true position of the cluster. Such a procedure excludes nodes, which are located in the secondary $\delta$ minima, arising due to the age-metallicity-extinction degeneracies in the 3-D parameter space.

## 3. RESULTS AND DISCUSSION

The results of parameter determinations of clusters are provided in Figures 1 and 2 for color excess values $E_{B-V} = 0.1$ and 1.0, respectively. In each panel the differences of parameters (determined minus true) are shown in groups of five filled circles, the middle circle is positioned at the true age of the cluster, i.e., the circles indicate parameters determined at $\delta_{\rm max}$ threshold values from 0.01 to 0.05 mag, with a step of 0.01 mag, plotted from left to right. Open and black circles correspond to the *UBVRI* and *UBVRIJHK* passband set cases, respectively. Errorbars indicate standard deviations of the determined parameters and characterize the integrated 'size' of the $\delta \le \delta_{\rm max}$ 'island' in the corresponding parameter space.

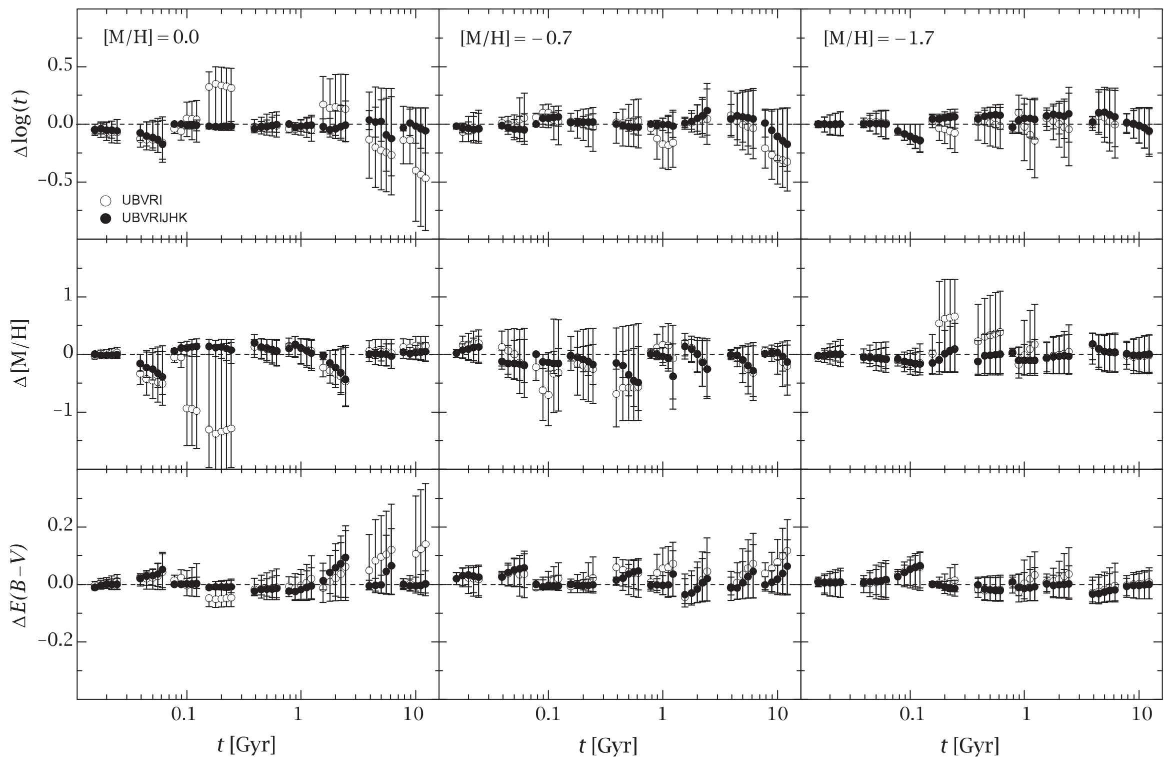


**Fig. 1.** Star cluster parameter determination results for star clusters with the following parameters: age, $t$ = 0.02, 0.05, 0.1, 0.2, 0.5, 1, 2, 5 10 Gyr; metallicity, [M/H] = 0.0, −0.7, −1.7 (left, middle and right panels); color excess, $E_{B-V} = 0.1$. Differences of the parameters (determined minus true) are shown in groups of five filled circles, the middle of which is positioned at the true age of a star cluster. Within a group, from left to right, the circles correspond to the quantification results derived for $\delta_{\max}$ from 0.01 to 0.05 mag, with a step of 0.01 mag. Open and black circles correspond to *UBVRI* and *UBVRIJHK* passband set cases, respectively. Error-bars indicate the standard deviations of the derived parameters.

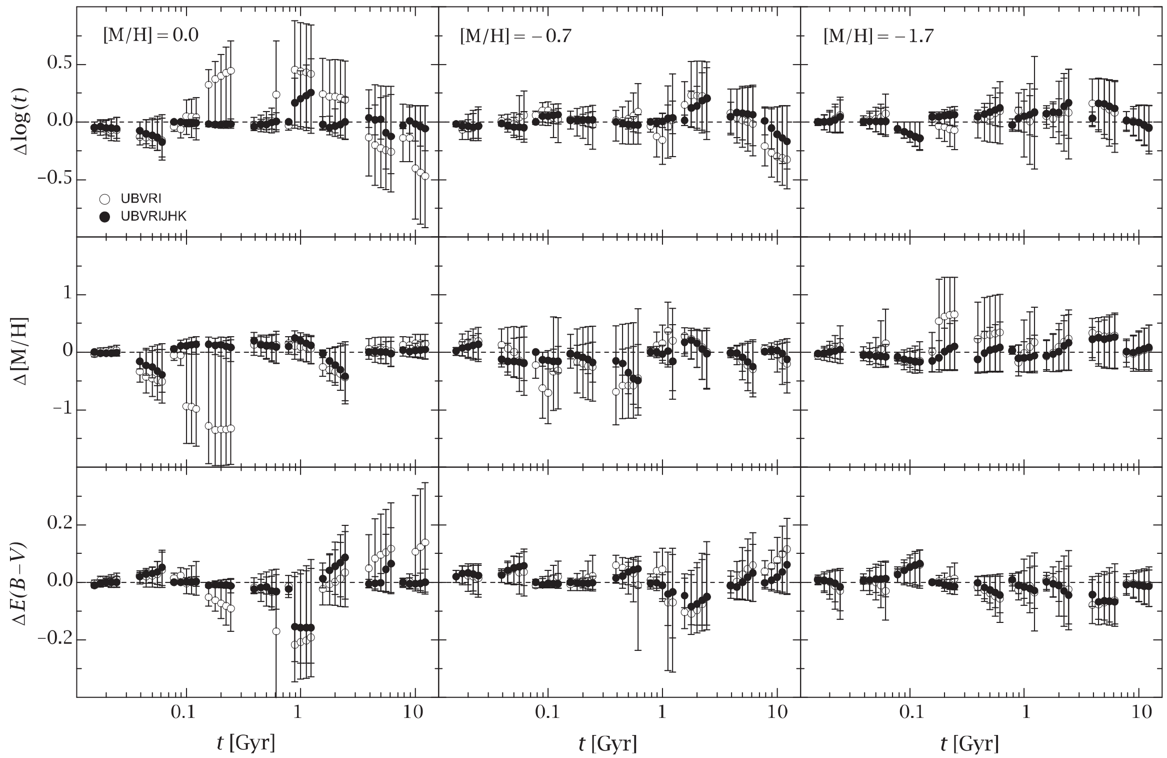


**Fig. 2.** The same as in Figure 1, but for the case of color excess $E_{B-V} = 1.0$.

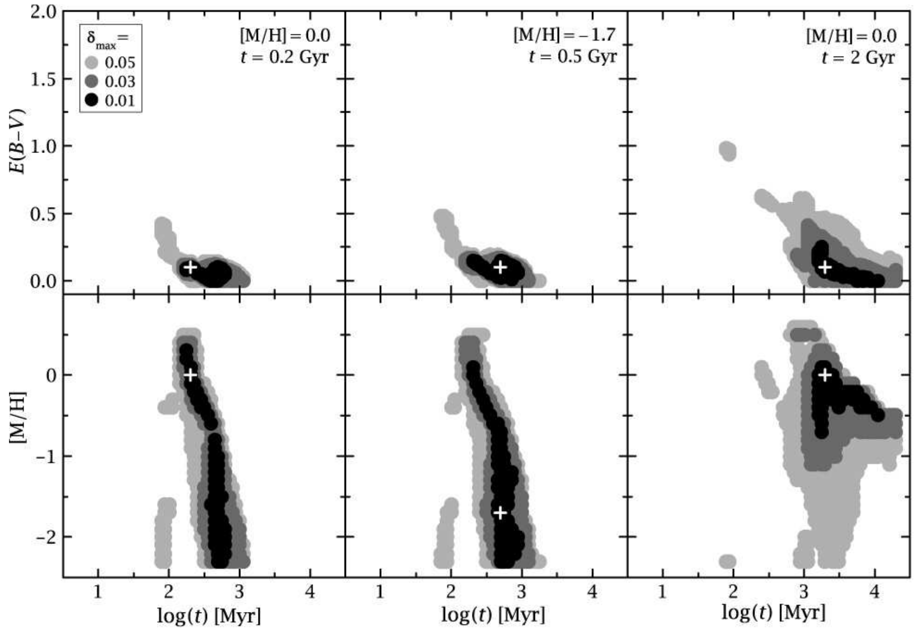


**Fig. 3.** The distribution of the quantification quality criterion, $\delta$, in projection onto the $E_{B-V}$ and [M/H] vs. $\log(t/\mathrm{Myr})$ planes for the clusters with the parameters: $E_{B-V}$ = 0.1, [M/H] = 0.0, $t$ = 0.2 and 2 Gyr (left and right panels); $E_{B-V}$ = 0.1, [M/H] = −1.7, $t$ = 0.5 Gyr (middle panel) for the case of *UBVRI* passband set. The true positions of cluster parameters are marked by a white "plus" symbol. Black, gray and light-gray shaded areas correspond to $\delta_{\max}$ = 0.01, 0.03 and 0.05 mag, respectively.

It is clearly visible in both Figures 1 and 2, that additional usage of *JHK* passbands significantly improves the precision of cluster parameter determination with respect to the *UBVRI* passbands alone. Especially good results are in the case of the small color excess, $E_{B-V}$ = 0.1, value. Note, that strong age-metallicity degeneracies at ages $t$ = 0.1, 0.2 and 10 Gyr, which are present in the *UBVRI* case, completely disappear in the *UBVRIJHK* case. A similar, but a slightly weaker effect is also visible for models of ages $t$ = 2 and 5 Gyr. However, if objects are highly reddened, $E_{B-V}$ = 1.0, there are still notable parameter degeneracies for some cases. The strongest age-extinction degeneracy is for clusters with: $t$ = 1 Gyr and [M/H] = 0.0; $t$ = 2 Gyr and [M/H] = −0.7; $t$ = 5 Gyr and [M/H] = −1.7. Actually, the quantification results of the last case are much more accurate, when SSP models older than 15 Gyr are not included in the calculation of the average.

The impact of adding the *JHK* passbands to the *UBVRI* system on the accuracy of the quantification of cluster parameters is illustrated in Figures 3–10 for the clusters of ages $t$ = 0.2, 1, 2, 5, 10 Gyr for solar metallicity, and $t$ = 0.5 Gyr for [M/H] = −1.7. The figures display cluster parameter quantification maps at the threshold levels of $\delta_{\max}$ = 0.01, 0.03 and 0.05 mag.

In Figures 3 and 5 for the *UBVRI* set, the left and the central panels look very similar, although the left panel displays quantification map of a cluster with $t$ = 200 Myr and [M/H] = 0.0, while the central panel – for a cluster with $t$ = 500 Myr and [M/H] = −1.7. This means that due to age-metallicity degeneracy for both clusters we obtain similar and wrong parameters. However, the situation changes,

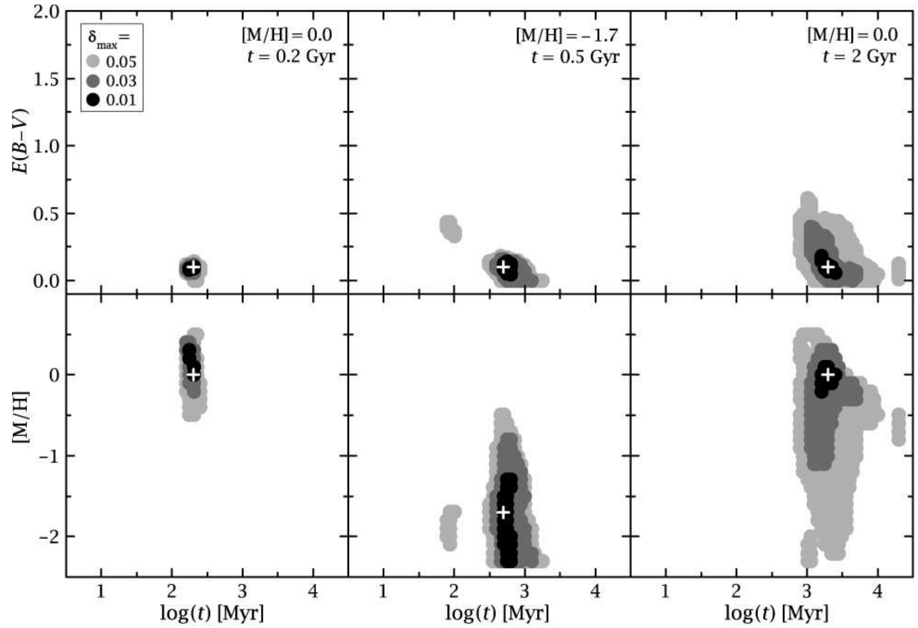


**Fig. 4.** The same as in Figure 3, but for the case of $UBVRIJHK$ passband set.

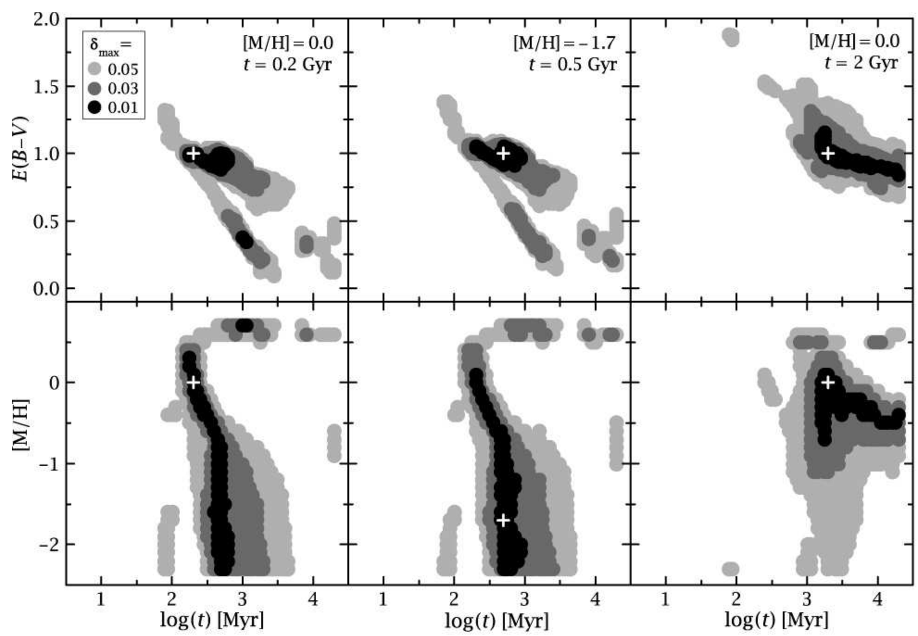


**Fig. 5.** The same as in Figure 3 for the case of $UBVRI$ passband set, but for $E_{B-V} = 1.0$.

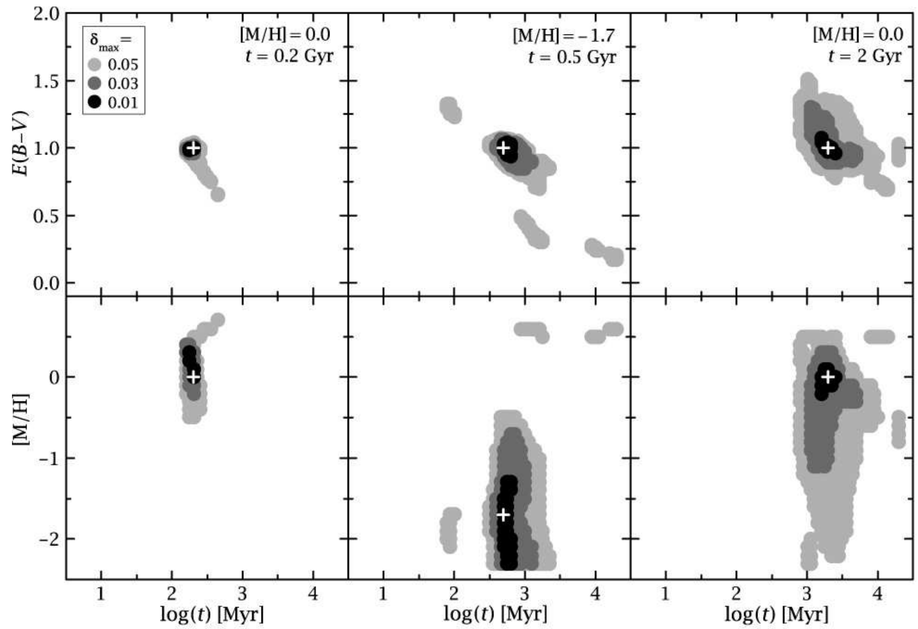


**Fig. 6.** The same as in Figure 5, but for the case of *UBVRIJHK* passband set.

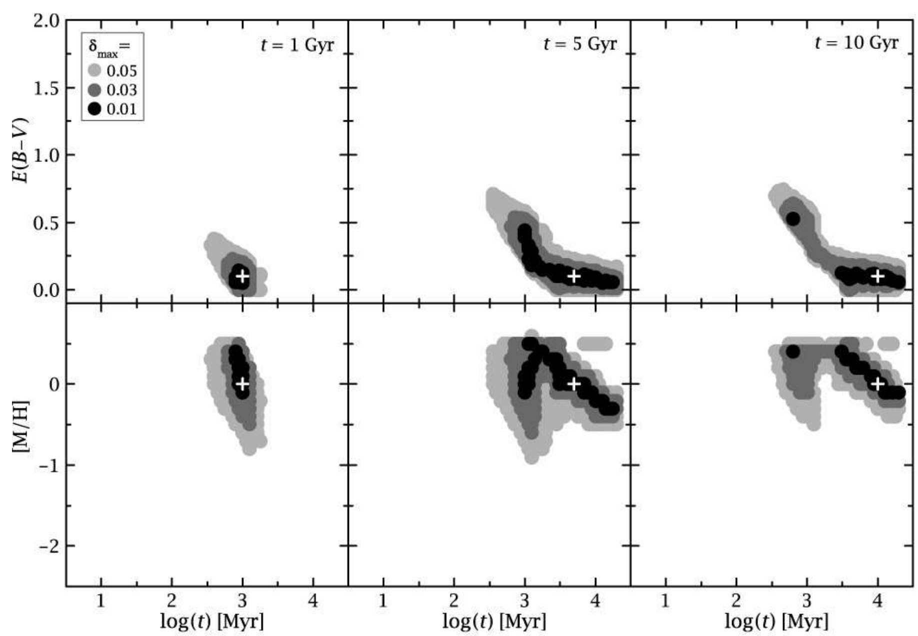


**Fig. 7.** The same as in Figure 3 for the case of *UBVRI* passband set, but for the star clusters with the following parameters: $E_{B-V} = 0.1$, [M/H] = 0.0, $t$ = 1, 5 and 10 Gyr.

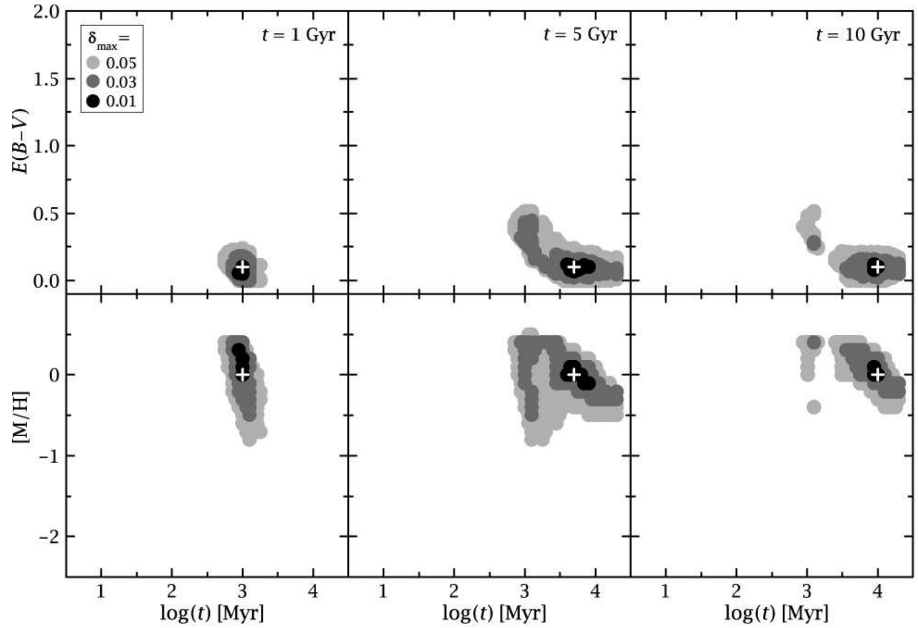


**Fig. 8.** The same as in Figure 7, but for the case of *UBVRIJHK* passband set.

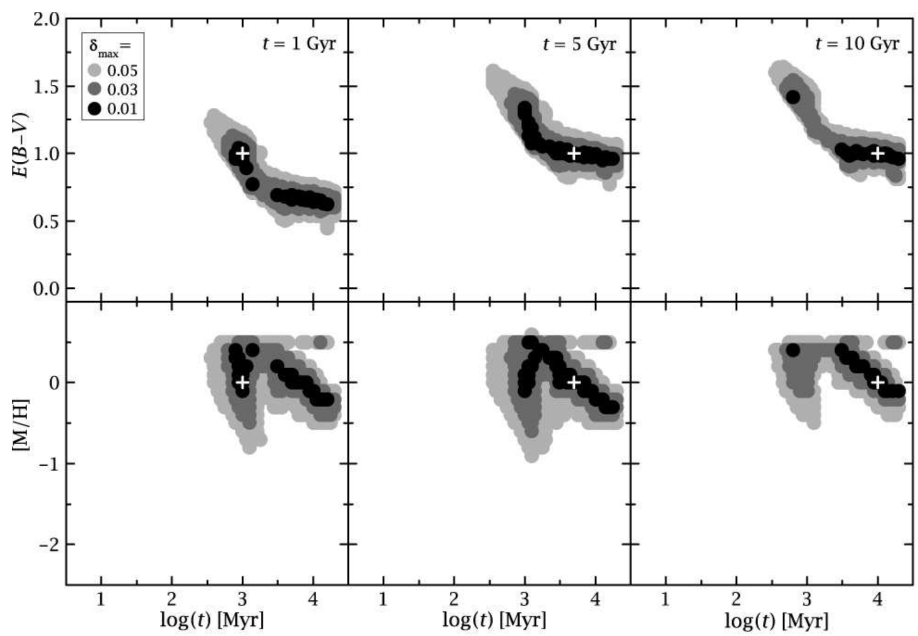


**Fig. 9.** The same as in Figure 7 for the case of *UBVRI* passband set, but for $E_{B-V} = 1.0$.

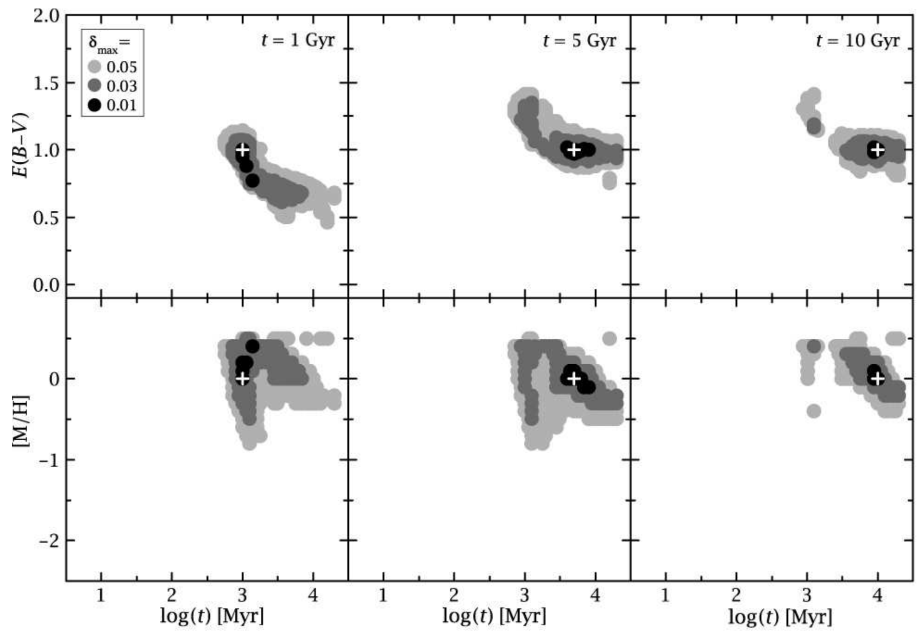


**Fig. 10.** The same as in Figure 9, but for the case of *UBVRIJHK* passband set.

when the *JHK* magnitudes are added. Figures 4 and 6 display quantification maps of the same clusters, but for the *UBVRIJHK* passband set. Note, that degeneracies disappear, even at $\delta_{\max} = 0.05$ mag level.

An interesting example is the cluster with the parameters $t = 2$ Gyr and [M/H] = 0.0. Figures 1 and 2 show that the addition of the *JHK* magnitudes improves the age determination, but $E_{B-V}$ determination becomes of lower accuracy, comparing to the *UBVRI* set alone. Rightmost panels in Figures 3–6 clarify this situation. In the *UBVRI* case, strong age-metallicity degeneracy takes place: note the additional 'tail' of suitable SSP models in the $E_{B-V}$ vs. $t$ plane towards older ages and lower $E_{B-V}$ values. This helps to compensate the influence of SSP models at higher $E_{B-V}$ values, and the quantification produces a 'correct' reddening. In the case of *UBVRIJHK*, no such 'tail' is seen, therefore the determined $E_{B-V}$ value is shifted from its true position.

Figures 7–10 display three similar cases of parameter degeneracies for clusters of solar metallicity and ages $t = 1$, 5 and 10 Gyr. Only the 10 Gyr age sample is sensitive enough to the addition of the *JHK* passbands, when parameter degeneracies become broken even at $\delta_{\max} = 0.05$ mag level. On the contrary, for the ages of 1 Gyr (except for the case of $E_{B-V} = 0.1$; see Figures 7 and 8) and 5 Gyr, parameter degeneracies exist even for $\delta_{\max} = 0.01$ and 0.03 mag, respectively. This implies, that the overall accuracy of cluster color indices must be better than 0.03 mag, which is rather difficult to achieve in infrared photometry.

We also investigated separately the influence of each infrared passband to the parameter determination precision with the purpose to find a minimum passband set, which would be sufficient for the quantification of clusters. The result is that all three color indices ($V$–$J$, $V$–$H$, $V$–$K$), added to the *UBVRI* photometric system separately, reduce the quantification errors, but $V$–$K$ is most important.

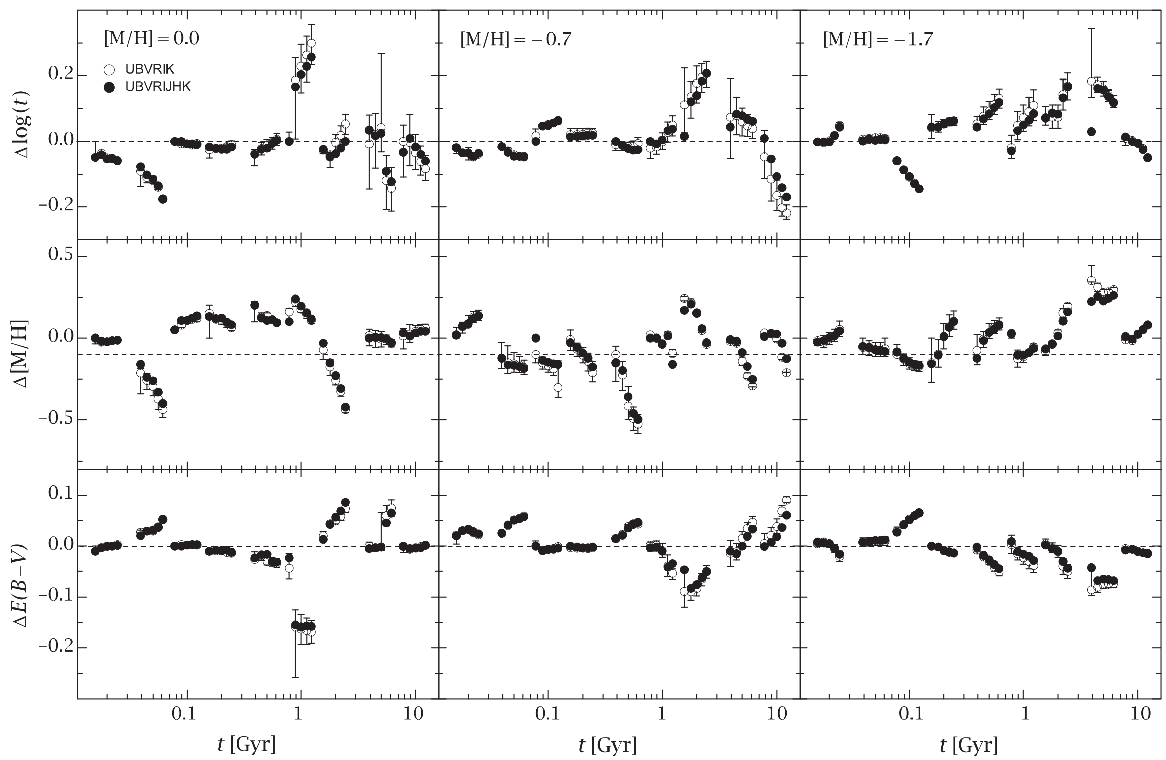


**Fig. 11.** Comparison of star cluster parameter quantification results for the case of color excess $E_{B-V} = 1.0$ (see Figure 1 for star cluster details). Black filled circles correspond to the case of *UBVRIJHK* passband set, open circles – to the *UBVRIK*. The error-bars show the sensitivity of determined cluster parameters to the artificial shift of the $V{-}K$ color by $\pm 0.03$ mag.

Figure 11 displays the quantification results for clusters using the *UBVRIJHK* (filled circles) and the *UBVRIK* (open circles) passband sets, both pictures are quite similar. Thus the *K* passband helps to solve majority of the parameter degeneracy problems. The error-bars in the *UBVRIK* case show the sensitivity of the parameters to the change of $V{-}K$ by $\pm\,0.03$ mag.

Recently an updated version of stellar isochrones, compared to those used in PÉGASE, has been released by the Padova group, which includes a more accurate treatment of thermally pulsating AGB stars (Marigo et al. 2008). It has been shown that the interpretation of integrated colors of unresolved galaxies, by applying galaxy populations synthesis method and the new isochrone set, can be significantly altered due to improved models of AGB stars (e.g., Tonini et al. 2008). In the case of single stellar population analysis of star clusters one can expect similar changes. Our method of the parameter degeneracy analysis, which is much simpler than the methods described in the literature (see, e.g., de Grijs et al. 2005), can be used to study the effects AGB stars on cluster colors by intercomparing parameter degeneracies in various SSP model frameworks.

## 4. CONCLUSIONS

We conclude that additional photometric information from the *JHK* passbands can significantly improve the accuracy of the determination of cluster parameters based on the PÉGASE SSP models, in comparison with the results when photometry only the *UBVRI* passbands is available. Even one additional *K* passband can improve significantly the capability of the *UBVRI* photometric system to eliminate age-metallicity and age-extinction degeneracies in the majority of the investigated cluster models, when the overall accuracy of color indices is better than $\sim$0.05 mag.

Note, however, that this condition of photometric accuracy is broken for young low-mass star clusters, where the stochastic effects, arising due to a few bright stars, dominate (e.g., Cerviño & Luridiana 2004; Deveikis et al. 2008). This implies, that even in case of ideal photometric calibrations, the uncertainty of cluster colors due to stochastic effects limits the applicability of SSP model fitting to derive evolutionary parameters of low-mass star clusters.

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